Journal of Environmental Management xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Bio-fixation of flue gas from thermal power plants with algal biomass: Overview and research perspectives

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ARTICLE INFO

Keywords:
Flue gas
Thermal power plant
Microalgae
Bio-fixation of CO_2
Photosynthesis
Bioreactors

ABSTRACT

Rate of energy production is reflecting growth of nations and most of energy produced from the coal and natural gas-based thermal power plants (TPPs). Flue gas (point sources of emission) are main exhaustible form of gases that come from thermal power plants and are continuously promoting climate change and various environmental problems in global scenario. The present available technologies of flue gas treatment are energy and cost-intensive process. Among the available techniques for fixation of flue-gases at sustainable part, microalgal bio-fixation of flue gas is an alternative promising and competent technology with assurance of eco-friendly path of low energy and low-cost solution for pollution abetment with production of value added products. According to mechanism involves during photosynthetic process of microalgae, it utilizes atmospheric CO_2 and CO_2 from flue gases for their growth. Past, present and future treatment technologies for flue gas with their challenges are discussed. Recent experimental studies and commercially available bioreactors are very particular for bio-fixation of flue gas from thermal power plants are also reviewed with their future perspectives. The commercial viability of process with specific microalgal strains and utilized biomass for further value-added products are suggested with future limitations.

1. Introduction

Energy plays an important role in the development of any nation and with increase in energy generation and consumption, the overall gross domestic products (GDP) growth rate also increasing. The gap between demand and supply of energy is increasing gradually. Most of the nations required huge amount of energy for their industrialization. To meet out this gap, more power generation has to be done with high capacity of thermal power plants. Thermal power plants (TPPs) are the significant means for the generation of power not only in developing nation but at worldwide. Coal and natural gas are the main fuels used in TPPs and a considerable amount of greenhouse gases (GHGs) emit from them. The exhaustible gases known as flue gases and it comprises various rational derivatives of CO_X, NO_X, SO_X gases and toxic metals (Pb, Cd, Mn, Se, Cr, Zn, Hg, As, Co, Cu, Ni, Sb, Se, Sn, V) (Huang et al., 2004; Napan et al., 2015) and air-borne particles like fly ash, soot, suspended particulate matter and other trace gas emissions comprises to come out from these TPPs (Deng et al., 2014; Saarnio et al., 2014; Chandral et al., 2013). Toxic metals diversity and their concentration depend on the type of coal utilized in TPP. Cuellar-Franca et al. (2015) reviewed that about 40% of the worldwide CO_2 emissions are caused from power production in fossil fuel-based TPPs. Furthermore, Kuramochi et al. (2012) assessed and evaluated that most of CO_2 based flue gas emissions from industrial sector (iron and steel manufacturing, petroleum refineries, cement production, chemical and petrochemical) at global level *i.e.* 6.6 Gt/year. CO_2 is estimated as a major component in industrial flue gas (3–30% CO_2) (Bhola et al., 2014).

Flue gases have numerous negative impacts on health of biotic flora and fauna and their surrounding environment. The release of suspended particulate matter causes respiratory ailments to human beings and animals and gets deposited on the plants which affect the photosynthesis. The SOx and NOx emissions affect the building structures and monuments due to the corrosive reactions (Pokale, 2012; Chen et al., 2015). The CO_2 emission contributes towards global warming and global climate change. The impacts include sea level rising, melting of glaciers, climate alteration and changes in the local ecosystems. Instead of coal-fired and natural gas based TPPs, some other minor sources are available which generates flue gases (Ali et al., 2017; Yan et al., 2016)

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https://doi.org/10.1016/j.jenvman.2019.01.043
Received 27 May 2018; Received in revised form 3 December 2018; Accepted 15 January 2019
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includes biomass based TPP and boilers (Qiu, 2013; Colom-Diaz et al., 2017), district heating sources (Wojdyga et al., 2014), coal-fuelled boilers (Kubica et al., 2017), incinerators (Zhang et al., 2017; Mukherjee et al., 2016), liquefied natural gas (LNG) fired power plants (Xu and Lin, 2017), circulating fluidized bed reactors (Wang et al., 2016), waste material based power plants (Mortensen and Gislerod, 2014), pulverised fuel-fired power plant (Myllari et al., 2017) and industrial flue gases (Guo et al., 2017).

The universal end product of the combustion is CO_2, which is one of the major gas responsible for the global climate change and it comprises 12–20% of flue gas (Aslam et al., 2017). To capture this emitted gas from the TPP, various technologies have been developed like as dry systems, semi-dry systems and wet systems (Rui de Paula et al., 2017). Some of the technologies used for flue gas treatment includes electrostatic precipitator (ESP) (Loschau and Karpf, 2015), cyclones (Baltrenas et al., 2015), fabric filters (Hajar et al., 2015), selective catalytic reduction (SCR) and non-selective catalytic reduction (NSCR) (Guo et al., 2012; Mukherjee et al., 2016), semi-dry flue gas desulphurisation (FGD) and limestone-gypsum FGD (Cottrell, 2016), spray dry absorber (Kedrowski et al., 2010), scrubbers (North London Waste Authority, 2014), high energy electron beam (Gogulancea and Lavric, 2014; Basfar et al., 2010), non-thermal plasma technology (Urashima and Chang, 2000) and many other technologies. The selection of CO_2 capture and storage technology depends on the types of fuel quality and CO_2 generating TPP. There are various technologies available to capture CO_2 are mentioned in Fig. 1. Although pro-combustion process is more mature and can easily adapt in TPP, low CO_2 concentration affects and reduce the capture efficiency. Whereas, pre-combustion process requires high capital and operating cost for the sorption of CO_2. Similarly, oxy-fuel combustion also drops efficiency and requires high amount of energy as well as creates corrosion problems (Leung et al., 2014). In geological storage, after capturing and compressing of CO_2 it shipped or pipelined to geological storage sites. These sites involve injecting of CO_2 into deep saline aquifers, depleted oil or gas reservoirs and coal mines at depths range of 800–1000 m (Cuéllar-Franca et al., 2015). This is an emerging method for the oil and gas industry but transportation of CO_2 at geological site enhanced capital and operating cost similarly, fear factor of leakage are also main concerns of CO_2 storage at geological site.

Among these technologies, biological fixation of flue gas using microalgae have been recognized as the future alternative with high capacities to fix CO_2, which is 10–15 times more efficient than terrestrial plants under the mechanism of photosynthesis. This technology is more efficient in the fixation of CO_2 of flue gas because CO_2 released from the TPPs can be fed directly into the microalgae culture as the purification of flue gas is not required every time. Similarly, flue gas components other than CO_2 like oxides of sulphur and nitrogen with heavy metals can be effectively used as nutrients for microalgae cultivation (Zhang, 2015). For the production of carbohydrates, lipids, and proteins, microalgae require CO_2, light and nutrients (nitrogen, phosphorous and minerals). Flue gas from TPP is considered to be the rich source of CO_2 for microalgae in integration with nutrient sources for accelerated growth. Heavy metals have the great potential to bind in microalgae cells and also can be catalysed biofuel production by altering the lipid accumulation into microalgal cell and other microalgal derived products (Pavlik et al., 2017). Microalgae cultivation system with TPP is a promising clean and sustainable approach because somehow it has a potential to reduce the CO_2 emission level, due to fossil fuel use. It is an economic and environment friendly approach because CO_2 emission reutilized by fixation through biomass. Furthermore, potential uses of microalgal biomass after sequestration includes bio-diesel production and many more value added end products (Kothari et al., 2017; Ahmad et al., 2018) makes it novel system's component of nature without any harm for society. There are three routes of utilization of microalgal biomass for energy production: (i) direct combustion for power generation; (ii) biochemical conversion for biogas, bio-ethanol, bio-hydrogen, and (iii) thermochemical conversion for syngas, bio-oil *etc.* (DOE, 2016).

Hence, bio-fixation of the flue gas from thermal power plants using microalgal biomass taken as a broad objective for this review. Influencing algal growth parameters with flue-gas composition also investigated on the base on experimental as well as reviewed articles available. Furthermore, microalgal species have a potential candidature for bio-fixation of CO_2 and other nutrients from flue gas, also reviewed and discussed with specific remarks for sustainable solution.

2. Flue gas

Use of non-conventional sources of energy such as coal and natural gas in the TPPs lead to the emission of hazardous air pollutants in the form of gas called flue gas (Gogulancea and Lavric, 2014). According to the world coal association, about 41% of global electricity is provided by the coal-based TPPs and the imposition of the coal is projected to raise 15% until 2040. This rise is mainly because of growing energy

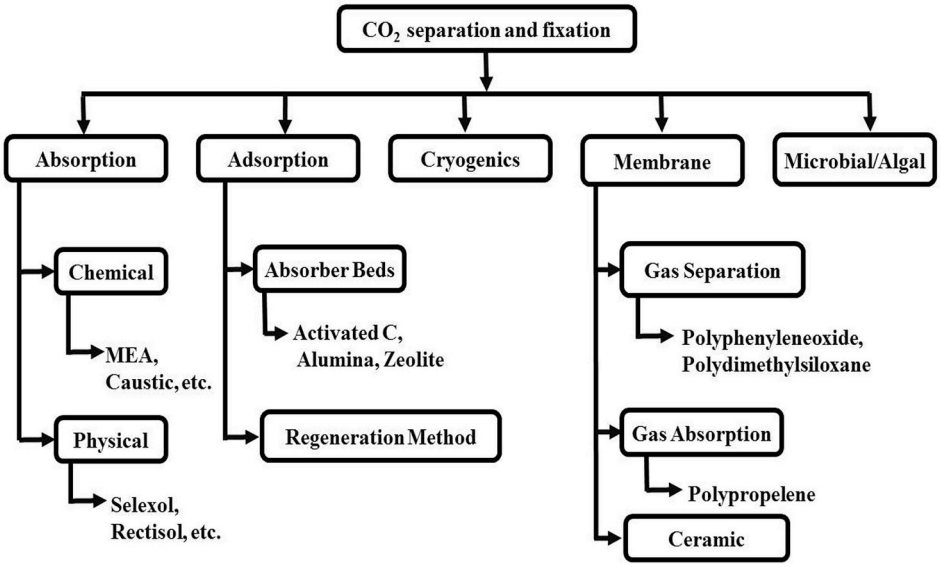

Fig. 1. Different technologies for carbon dioxide separation and fixation (Leung et al., 2014; Cuellar-Franca et al., 2015).

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Table 1
Flue gas composition in various Thermal Power Plants (TPPs).

Methods of combustion in thermal power plants	Flue gas composition (%)								References
	O_2	N_2	CO_2	H_2O	CO	SO_2	NO_X	Dust	
Pulverised coal combustion	6	76	11	6	–	–	500–800	5–20	Zevenhoven and Kilpinen (2001);
Waste incineration system	7–14	–	6–12	10–18	0.001–0.06	200–1500	200–500	0.2–15	Testo (2004); Hwang et al. (2017)
Coal fired integrated coal gas cycle (IGCC)	12	66	07	14	–	10–200	10–100	> 0.02	
Gas fired combined cycle	14	76	3	6	–	–	10–300	–	

needs of the Asian countries (Rui de Paula et al., 2017) as well as throughout the world such as Germany, Austria, Israel, USA, Australia (Zhang, 2015). Composition of the flue gas depends largely on the type of fuel used in TPPs and coal combustion process, and the coal-based plants emit flue gases somewhat different in composition in comparison with the natural gas-based power plants. The composition also depends on the combustion conditions such as air ratio value, volume of combustion chamber, combustion temperature, and many more as discussed in Table 1. The flue gas should be treated with suitable treatment technology before being discharged directly to the atmosphere from the exhaust, so that the hazardous air pollutants can be filtered off. The gas before the treatment is called raw gas and the gas obtained after the treatment is called clean gas. The main components present in a certain quantity of flue gas are carbon monoxide (CO), CO_2, oxygen (O_2), water vapours (H_2O), nitrogen and their oxides (N_2, NO, NO_2, sum formula of NO_X), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), hydrocarbons (C_XH_Y), ammonia (NH_3), hydrocyanic acid (HCN), volatile organic compounds (VOCs), solids (dust, soot) (Testo, 2004; Packer, 2009).

These pollutants composition directly shows their impacts of flue gas on the environment. All these by-products release from the stack of TPPs are undesirable and indeed, are the reasons for the global climate change all over the world. Pollutants from the stationary combustion process results in formation of the photochemical smog, acid rain, and disrupt the heat balance which ultimately leads to the greenhouse effect. Photochemical smog and acid rain are the most common effects on flora and fauna as well as stone buildings and monuments (Pokale, 2012). Due to these pollutants, the particulate matters are usually formed by the combination of the emitted fly ash and the carbon content (Nakomcic et al., 2014). The emissions of the particulate matter released in the atmosphere degrade soil and water (Chmieleswski, 2009). Whereas, emissions of the VOCs in atmosphere can lead to ground level photochemical ozone formation, which has negative impacts on the human health and environment (Basfar et al., 2010) (Fig. 2.).

The coal used for combustion in TPPs strongly contributes to global climate change because of elevated carbon content of coal, which in turn, causes the emission of CO_2 in atmosphere. The flue gas components come under the category of environmental xenobiotics, which are foreign substances to biological system. The xenobiotics are substances which did not exist in the nature before human involvement and synthesis and their presence in the environment can cause perilous and labile conditions since their hazardous effects on the ecosystems are often unpredictable (Bulucea et al., 2015).

2.1. Flue gas treatment technologies: past, present and future

Flue gas treatment systems (FGTS) are referred to ranges of processes to reduce the number of pollutants emitted from the burning of fossil fuels at TPP. According to literature available, FGTS concerns mainly focused on to control the sulphate impacts on the environment in 1990's but in 20's as the research and development sectors increased their focus on discovering new devices/techniques with more advanced objectives for pollutants removal from flue gas at various degree of levels by chemical reactions and electrostatic precipitation provides a clear vision on future trends in concern area (Bamber, 1990; Thitakamol et al., 2007). Presently, demand of thermal energy and development of technologies of FGTS are more prone to control further processing steps.

To mitigate the harmful impacts of flue gases (air pollutants), TPPs should treat the gases before discharging directly into environment. The TPPs should install FGTS along with the energy recovery systems (ERS). FGTs are categorized into three basic systems: dry systems, semi-dry systems and wet systems (Fig. 3.). Table 2 **is** delineating a comprehensive classification of the FGTS along with process, advantages and disadvantages. The flue gas derived from the dry and semi-dry systems has temperature significantly higher than the flue gas derived from the wet systems and it is above the dew point of the water. Hence, formation of plume is more in case of wet systems and results in more plume visibility in comparison with the dry and semi-dry systems (North London Waste Authority, 2014).

Technologies involved in removal of waste materials/streams from flue gas and these technologies with pros and cons are overviewed in Table 3. Hence, treatment of the flue gas is good but the comprehensive scenario of treatment of flue is creating various environmental problems by involvement of water, electricity and final decomposition stages. Therefore, a sustainable technology is required which abate flue gas and reliable way to forward. Biological fixation of flue gas can capture most of the components including CO_2, NO_X, SO_X and other trace elements. The transformation of TPP's flue gas into algal biomass can able to produce various value-added products such as nutraceuticals, pharmaceutical products and algal agriculture products. These value-added products can be valorized not only animal but also best for human consumption. The transformed algal biomass can be a best source of renewable energy application by advanced energy conversion technologies such as hydrothermal liquefaction, bio-compressed natural gas (bio-CNG) *etc.*(Fig. 5.). Hence, flue gas fixation using microalgae is the versatile tool in comparison with the other technologies.

Apart from these, FGTSs need a huge amount of hazardous chemicals which are used in various treatment processing steps of flue gas. These all are listed in Table 4 and are responsible for deterioration of environmental abiotic components due to chemical compositions. Lime, bicarbonates derivatives caused water and soil pollution. Ammonia is toxic gas and its derivatives can have potential to produce various carcinogens. Therefore, FGTSs are not clean and green approach, and use of these in processes harmful to environment at various degrees of levels.

3. Flue gas bio-fixation using microalgae

There are numerous technologies that have been developed to filter out the flue gas components (specially CO_2) before being discharged directly to the atmosphere, biological capture is one of them. The biological post-combustion capture of CO_2 can be done by using microalgal biomass, a diverse group of photosynthetic organisms. The ability of microalgae to do photosynthesis and grow rapidly in presence of CO_2 has resulted in the use of them for CO_2 bio-fixation. Microalgae use the CO_2 during the process of photosynthesis in order to grow and reproduce. The cells of microalgae contain about 50% of carbon and it

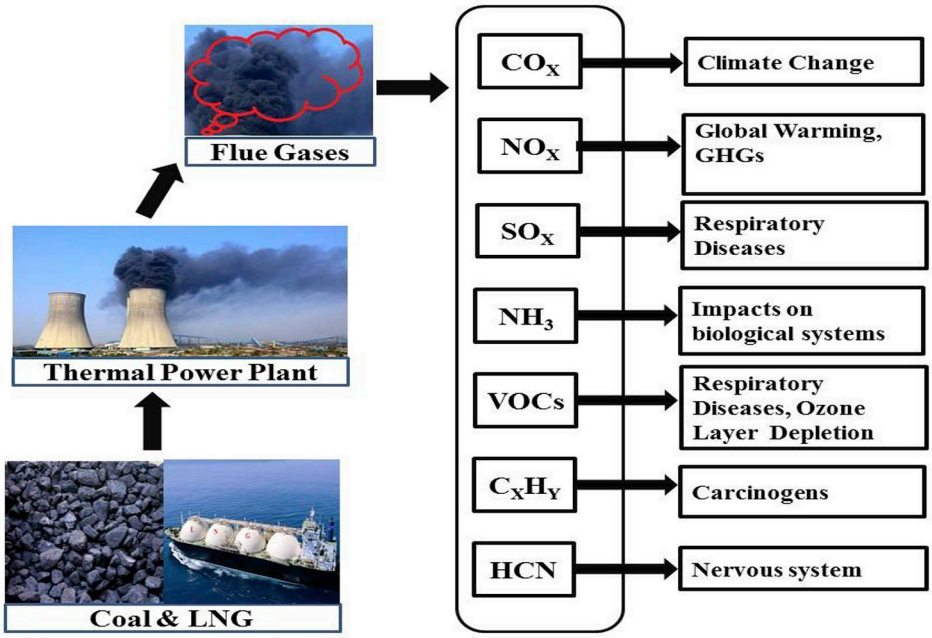

Fig. 2. Environmental impacts from flus gas emission.

has been reported that 1.8 kg of CO_2 is used by microalgae to produce the 1 kg of biomass (Pavlik et al., 2017). The efficiency of microalgae for bio-fixation is about 10–15 times more than the terrestrial plants (Zhang, 2015). The selection of type of microalgae strains depends on function of the biomass productivity, CO_2 fixation and tolerance capacity together with the lipid formation potential. Bio-fixation depends upon the tolerance of strains to the amount of CO_2 present in exhaust gas along with presence of SOx and NOx, and also to high temperature of the flue gas (Fig. 4.). The biomass of microalgae produced after bio-fixation can be used for production of biofuels, fodder for livestock, and for the generation of vitamins and colorants (Bhola et al., 2014), omega fatty acids (Passell et al., 2013; Klinthong et al., 2015). Advantages of using microalgae for the flue gas bio-fixation according to available recent experimental studies and findings are given in Table 5. Pure CO_2 is not required for the fixation. Flue gas from the stack can be directly applied to the microalgae culture and the microalgae can convert the different gases from flue gas into useful nutrient for biomass. Thus, separation of the CO_2 from flue gas can be achieved significantly (Sharmila et al., 2014). Some of components of flue gas such as SOx and NOx can be used as nutrients for the growth of the microalgae (Li et al., 2011). Biomass from algae is not a contributing factor in greenhouse gas emissions but help in remediation of this. So, renewable energy options are the solutions for globally identified environmental issues. It is assessed that reduction in transportation emissions are possible, which are contributing upto 27% in emission cycle, if we go for renewable biofuels from biomass (Antoni et al., 2007). Use of utilized algal biomass after bio-fixation of flue gas, contribute to net zero value of CO_2, SOx and other atmospheric contaminants more than fossil petroleum fuels (Miao et al., 2004). Therefore, attention towards bio-fixation of flue gas with algae and utilization of that biomass for bio-fuels as well as other end-products, part of recent researches in terms of viable and cost-effective approach.

3.1. Microalgae species for CO_2 bio-fixation

There are some species which can grow competently under the natural day-night cycle and thus can be used for large-scale outdoor culture systems. Besides, there are strains which can use the CO_2 directly from the flue gas for the microalgal biomass production, known as CO_2 bio-fixation agents. Similarly, few species requires compounds of sulphur and nitrogen (SO_X and NOx) for their growth as they act as a source of nutrients for them (Kothari et al., 2012; Kothari et al., 2013). Some species have high CO_2 removal rates while some are more specific in the removal of SOx, NOx and VOC'S like as *Nannochloropsis salina, Desmodesmus* sp., *Chlorella fusca* and *Spirulina* sp. (Malek et al., 2017; Aslam et al., 2017;Duarte et al., 2017).

The selection of microalgae species is very important in this regard, Hanifzadeh et al. (2017) studied the cultivation of two microalgal strains under the supply of two concentrations of CO_2 (5% and 15% v/v). They found that maximum CO_2 fixation was with for *Chlorella vulgaris* in comparative to *Scenedesmus obliqus*. So, *Chlorella vulgaris* is more potential species for CO_2 fixation emitted from industrial plants as cited by other researchers also (Duarte et al., 2017; Yadav et al., 2015; Gua et al., 2015; Kasiri et al., 2015). The CO_2 supply can be supplied directly to the microalgal cultivation through the photobioreactor systems. It is also important to note down that some compounds present in the flue gas can affect the efficiency of bio-fixation, even may be potentially toxic to some microalgae species. Hence, selection of species and the check to the supply of harmful elements present in the flue gas are the main parameters of consideration in this technology (da Rosa et al., 2015). Other factors which influence the efficiency of CO_2 bio-fixation by microalgae include pH of the culture, rate of CO_2 supply, light and temperature. Open pond and closed type photobioreactor are used for cultivation at large-scale production of microalgae also influenced by the flue gas flow rates. Closed systems are more efficient to minimize the CO_2 losses, nutrient losses from flue gas in the surroundings in comparison to open systems.

Table 6 clearly depicting the carbon fixation efficiency from flue gas and support that process is totally depends on the types of algal strains selected in associated with types of bioreactor, provides an efficiency of CO_2 removal approximately 85% but with open type it reduced to just half *i.e.* 42% only, experimental study investigated by Aslam and Mughal (2016).

3.2. Mechanism for bio-fixation of CO_2 from flue gas

Microalgae are photosynthetic organisms which capture light energy from the sun in form of the photons. Chlorophyll-a and b, carotene

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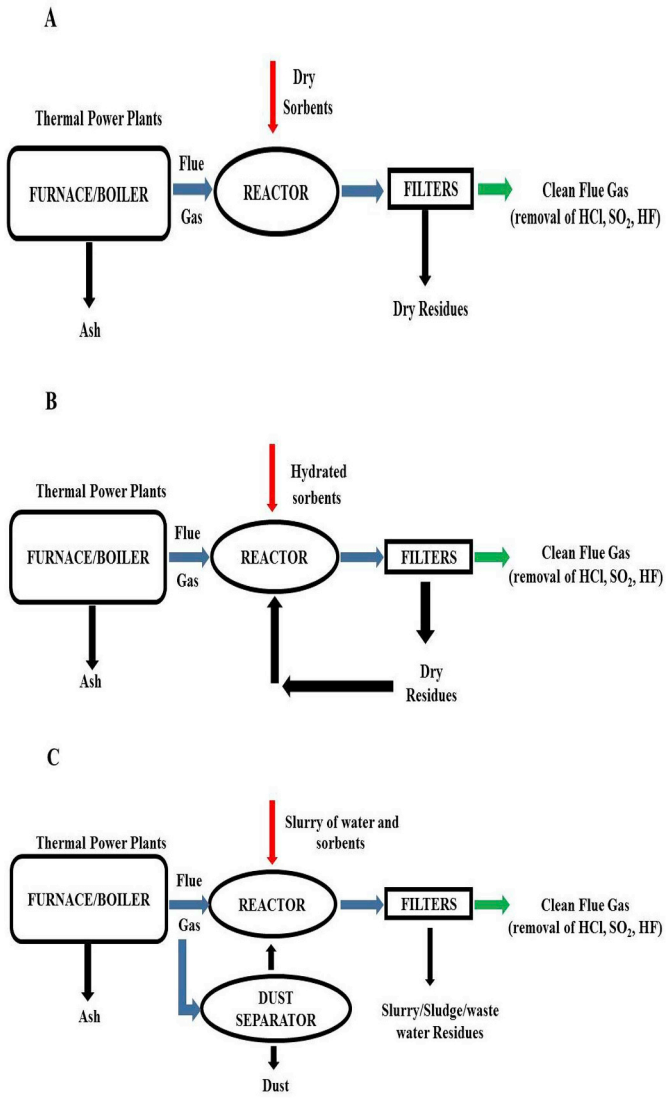

Fig. 3. Types of flue gas treatment systems: (A) Dry flue gas treatment; (B) Semi-dry flue gas treatment; (C) Wet flue gas treatment.

and xanthophyll pigments occurred in the microalgae cell. Among these, chlorophyll-a sole unit which converts light energy into chemical energy. Chloroplast has a photosynthetic reaction centre and this centre is a complex of several proteins, pigments and other co-factors that together execute the primary photon energy conversion reactions of photosynthesis (Yadav and Sen, 2017).

In microalgae, photosynthesis is a physicochemical process that converts CO_2 into valuable organic compounds by using light energy [Eq. (1)] and carbon fixation process takes place in chloroplast of algal cell. Stroma is a colourless fluid surrounding the grana within the chloroplast, and stroma contains grana, stacks of thylakoids and sub-organelles. Two type of stages performs in photosynthesis process *i.e.* light dependent reactions and light-independent reactions. Firstly, light-dependent reactions capture and store photon energy and convert adenosine diphosphate (ADP) and NADP + into energy-carrying molecules adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH); liberate oxygen molecule in thylakoids. In light-independent reactions, microalgae capture CO_2 and produce organic compounds through Calvin-Benson cycle by consuming ATP and NADPH, which are coming from light-dependent stage in stroma.

The dark reaction required CO_2 from atmosphere or flue gas point sources of thermal power plants (TPPs) and many more industries which has emission of CO_2. This CO_2 is converted into sugar/glucose with help of ATP and Ribulose-1, 5-biphosphate carboxylase/oxygenase (Rubisco) enzyme. The centers of carbon fixation are pyrenoids which sequestrate about 30%–40% of global CO_2 bio-fixation. This is sub-cellular microcompartment which is found inside of chloroplast of microalgae (Rosenzweig et al., 2017). The pyrenoid composed 90% part of photosynthetic enzyme Rubisco (Singh et al., 2016a,b) and this is a prime feature of the algal CO_2-concentration mechanism in the micro-algae cell, which supplies high concentration of substrate CO_2 to Rubisco. This makes algae higher efficient for carbon capture than that of terrestrial plants (Kroth, 2015; Rosenzweig et al., 2017). Rubisco has both activities of carboxylase and oxygenase, and 3 molecules of phosphoglycerate (PGA) are produced by reaction of one molecule of Ribulose-1, 5-bisphosphate (RuBP) with CO_2 and water (H_2O). PGA is the first carbon fixation product in the microalgal cell (Zhao and Su, 2014; Bhola et al., 2014; Cheah et al., 2015; Yadav and Sen, 2017). The morphology of pyrenoid may vary in species to species of microalgae such as *Chlamydomonas reinhardtii* and unicellular red algae *Porphyridium purpureum* have single pyrenoid in single chloroplast while dinoflagellates and diatoms may have large number of pyrenoid (Singh et al., 2016a,b). The complete microalgal carbon fixation mechanism with biofuel and value-added products production can be described by three step in Fig. 5.

$$6CO_2 + 6H_2O \xrightarrow{\text{Light energy (hv)}} C_6H_{12}O_6 + 6O_2 \quad (1)$$

Singh et al. (2016a,b) compiled a rigorous review on eukaryotic microalgal carbon fixation mechanism. Microalgae have able to modify their metabolic pathways according to availability of carbon source; autotrophic algae needs inorganic carbon source (CO_2) with salts and solar radiation while heterotrophic algae require organic compounds with nutrients as source of energy and mixotrophic algae stand between autotrophic and heterotrophic conditions. The sequestration of carbon in microalgal biomass from flue gas like CO_2 source is known two metabolic paths: first, inorganic carbon conversion by photosynthesis and second, is formation of calcium carbonate by calcification process. The transport of CO_2 in the microalgae cell occurs through passive diffusion and HCO_3^- ions by active transport (Fig. 5). However, plasma membrane and chloroplast is passage path of inorganic carbon before core processes of electron transport systems and Calvin-Benson Cycle. Plasma membrane has four inorganic carbon transporters and chloroplast have eight transporters. Carbonic anhydrase enzymes play a crucial role in catalyzing the interconversion of CO_2 and water [Eq. (2)] (Huang et al., 2017). The identification, localization and number of carbonic anhydrase enzymes different in various microalgal species. So, there are various genetic limitations with present scenario of genetic engineering of microalgae, which only hindered the understanding of carbon fixation mechanism of flue gas but also have been attracting to solve them.

$$HCO_3^- + H^+ \xrightarrow{\text{Carbonic anhydrase}} CO_2 + H_2O \quad (2)$$

4. CO2 sequestration using microalgae

To mitigate the greatest impact of GHG, the CO_2 must be captured and sequestered over long intervals of time (Sayre, 2010). One of the most important groups of organisms present on the earth is microalgae, as this produces about half of the atmospheric oxygen and consumes large amount of CO_2. Cyanobacteria, eukaryotic microalgae, green microalgae and diatom have a potential to capture CO_2 from three different sources: atmospheric CO_2, CO_2 emission from power plants and industrial processes and soluble carbonate. According to literature, CO_2 capture from flue gas emission is an easy on algal context but only a small number of algae are tolerant to high dosage of SOx and NOx present in flue gas. The flue gas produced from the power plant contains large concentration of CO_2, thus the species tolerant to high CO_2 used in

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Table 2
Different flue gas treatment systems (FGTS): Process, Advantages, Disadvantages and Challenges (EPA, 2011a, b; North London Waste Authority, 2014).

Flue gas treatment systems (FGTs)	Processes	Advantages	Disadvantages	Challenges
Dry systems: Most Used Technology	• Mixing of the dry sorbents and flue gas in the reactor.	• It is relatively simple to install and operate.	• The flue gases have to be cooled before going into the treatment line.	• Ability to meet more stringent future emission limit.
Lime and dry-carbonate based are the two most commonly used type of dry DFGT process. Lime is used for the removal of pollutants like SO_2, HCL, (HF), fine particles and mercury (Hg).	• Reaction between the sorbents and acid flue gas components.	• Space requirements are low.	• The excess reaction	
Dry flue desulphurisation technology is further classified into three types:	• Filter separation of the reaction products and acid free flue gas.			
a) Dry injection process: The dry hydrated lime is directly injected into flue gas stream.	• Disposal of the dry residues.			• Ability to handle changes in raw gas composition.
b) Spray dryer process: Finely atomized lime slurry is injected in the separate vessel where water from the slurry gets evaporated before the solids react with the flue gases.		• Capital investment and maintenance costs are relatively low.	stoichiometry characteristic of the dry system represents a significant running cost.	• Low chemical Consumption.
c) Circulating dry scrubbing process: In this process, the dry hydrated lime or dehumidified lime is injected into the separate vessel		• Flexible operation in terms of temperature and capacity.	• Significant quantities of residue generation increase disposal costs.	• Low residue production.
Semi-dry systems: Dry systems and wet systems are integrated to enhance the reaction between flue gases and the lime added to it.	• Mixing of the hydrated sorbents and flue gas in the reactor.	• Minimized use of lime as widely-used low-cost reagent.	• Capital and lifetime cost is higher than dry system.	• Ability to handle changes in raw gas composition.
The water is used in this system and can be injected directly into the gas stream or slurry of hydrated lime can be added, where the slurry has higher sorbent concentration.	• Reaction between the sorbents and acid flue gas components.	• High availability and low O&M cost due to simple design and operation.	• Moisture may cause problems if a fabric filter is employed later.	• Ability to meet more stringent future emission limit.
The need for the water in this system, to increase the rate of reaction with SO_2.		• Space requirements are moderate.		• Reduced contact with hazardous material.
System generates the solid residues which can be collected with the particulate matter collection equipments like bag house or ESP.	• Filter separation of the reaction products and acid free flue gas.	• The systems are more efficient than dry process.		
The addition of water serves two significant functions: the conditioning of the flue gas by increasing humidity and to decrease temperature of the gas.	• Disposal of the dry residues.	• Higher performance for removal of HCl.		
Wet systems: Advanced approach	• Separation of the dust particles from the flue gas.	• Lowest residue generation from acid gas removal.	• It produces ash-laden water.	• Limited plume visibility.
In this process, wet systems use calcium based absorbents, than gypsum is produced as a by-product, which is a valuable product in the field of construction industries.	• Mixing of the slurry (of the sorbents and water) and flue gas in the reactor.	• Proven technology for long run.	• The need to process the blow down produced by the different wash stages.	• Discharge of treated Wastewater.
The nozzles and injection locations are created in such a way that size and density of the slurry droplets can be optimized or enhanced by the system. Some part of the water gets evaporated from slurry in the system and results in saturation of the waste gas stream with water vapor. The oxides of sulphur dissolve in slurry and reaction takes place forming the neutral salts.	• Reaction between the slurry and acid flue gas components.	• Most reliable emissions control.	• Requiring high capital investment.	• Low electricity Consumption.
Wet systems produce wastewater that needs treatment before discharging to the outside.	• Scrubbers and filters separation of the reaction products and acid free flue gas.	• Operation with high availability.	• More complex to operate.	
Wet FGT plants are more efficient in flue gas cleaning and are more robust and have high flexibility in the sense of changes in raw gas composition	• Disposal of the slurry/sludge/ wastewater.	• High buffer capacity to handle peak variations.	• Skilled manpower to operate the system.	• Reduced contact with hazardous material.

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Table 3
Pros and cons for technologies of removal of waste materials from flue gases.

Technology	Material removed	Pros	Cons	References
Dry electrostatic precipitators	Dust and smoke	Removal of even fine dust particles from gas efficiently. Usable at high temperatures up to 450 °C. Low operating costs. Easy to handle the collected dry dust. Easy and efficient to collect high resistivity dust in moving-electrode type.	Dust can be re-introduced into the gas, called re-entertainment. Gaseous emission control is worst. High capital (equipment) costs.	Löschau and Karpf, 2015
Wet electrostatic precipitators (WESP)	Very fine dusts, aerosols, droplets, Particulate matter	Collection of particulate matter not suitable for dry ESPs, including sticky, moist, flammable, explosive, or high resistivity solids. Removal of very fine (submicron) particulate which dry ESP's cannot capture effectively. Because of the low-resistivity dust, there is no re-entrainment. High dust collection efficiency. It is possible to absorb other gases like SO_X, HCl simultaneously.	More costly than dry ESPs. Particulate matter is collected as slurry instead of a dry solid. Unsuitable for high value or recyclable materials. More expensive to handle and dispose Necessity of water treatment plant.	Löschau and Karpf, 2015
Fabric filters	Dust	High dust separation efficiencies of over 99.95%. Possibility of simultaneous separation of gaseous pollutants. Collection efficiency not affected by sulphur content of the combustion fuel. Less equipment cost than electrostatic precipitators.	In the presence of high acid or alkaline atmospheres, fabric life may be substantially shortened, especially at elevated temperatures. Maximum operating temperature is limited to 550 °F, unless special fabrics are used. Maintenance cost is high because of the high replacement cost of the bag filter. Widely used for industrial process with low or medium process gas.	Hajar et al. (2015)
Wet scrubbing	Acid gases, Sulphur dioxide (SO_2)	Residue generation from acid gas removal is lowest. Option of producing valuable materials such as gypsum, hydrochloric acid, and industrial salt. Efficiency to control SO_2 can reach upto 98%. Preferred process for coal-based power plants.	Requiring high capital investment because it includes many steps. More complex to operate, and requires specialist staff. High operating cost because of the liquid waste handling. Formation of scales in the absorber.	North London Waste Authority (2014)
Electron beams	NO_X, SO_X	No secondary waste generation. No catalysts, no heating and easy for automation. High efficiency of pollutants removal. Simultaneous removal of NO_X and SO_X. Good quality fertilizer as a by-product.	Relatively high energy consumption, especially for application to flue gas with high NOx and low SO_2 concentrations. Due to potential clogging of filters and its deposition in flue gas duct, filtration of by-product requires special attention. Large scale electron beams facilities are still required.	Chmielewski and Lick (2008); Basfar et al., 2008; Gogulancea and Lavric (2014); Basfar et al. (2010)
Spray dryer absorber (SDA)	Sulphur Oxides (SOx), Hydrogen Chloride (HCl), Particulate	Does not create any waste water discharge; thus eliminating the need of having any on site Water treatment. High reliability and availability for all the different loads. Acid-gas removal efficiency is high. Low power consumption. Operating and maintenance cost is low.	To deal with lime slurry is difficult and causes multiple problems, such as clogs in lines due to poor slurry mixing. Formation of wet bottoms because the exit temperature is too low.	Kedrowski et al. (2010)
Selective catalytic reduction (SCR)	NOx	Highest possible NOx removal efficiencies with the lowest possible ammonia slip. Destruction of dioxins and furans as well as oxidation of metallic mercury. High NO_X removal efficiency than SNCR. Installation is simpler.	Requirement of large volume of reagent and catalyst. Results in ammonia in the waste gas stream which may impact plume visibility. Possibility of erosion of the catalyst by flue gas. Investment cost is high than SNCR. Catalyst may get blocked or poisoned.	Guo et al. (2012); Mukherjee et al. (2016)

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Table 3 (*continued*)

Technology	Material removed	Pros	Cons	References
Selective non-catalytic reduction (SNCR)	NOx	No catalyst requirement in this process. Relatively simple installation and low investment cost. Lowest operating cost among various NO_X removal technologies. High levels of PM in waste gas streams are acceptable.	It can produce nitrous oxide (N_2O), thus contributes to the greenhouse effect. Controlling ammonia slip in SNCR systems is difficult. Temperature range of waste gas stream should be limited. Low efficiency than SCR. Requirement of downstream equipment cleaning sometimes.	Guo et al. (2012); Mukherjee et al. (2016)

the bio-fixation process (Sharmila et al., 2014). *Euglena gracilis* (5%–45%) and *Scenedesmus* (80%) are some of the most cited species tolerant for high concentration of CO_2 (Gaikwad et al., 2016). CO_2 removal or fixation efficiency of closed photobioreactors depend on species of microalgae, concentration of CO_2, design of bioreactor and operating conditions (Aslam and Mughal, 2016). Similarly, temperature of gases from TPPs also a challenging on practical scale because it needs to be cooled prior to use in the growth medium (Zhang, 2015). In a photobioreactor with microalgae culture, the difference between the CO_2 concentrations of the incoming and outgoing effluents defines the CO_2 removal efficiency (Table 6**)**. Thus, the CO_2 removal efficiency can be written as**:**

$$CO_2 \text{ Removal Efficiency} = (\text{Influent of } CO_2 - \text{Effluent of } CO_2)/ \text{Influent of } CO_2 \text{ X } 100\% \quad (3)$$

The fixation rate and growth of microalgae can be determined as the function of solar irradiance, efficiency of photosynthesis and surface-to-volume ratios. The equation can be written as:

$$X = I.(P.E).SV/E \quad (4a)$$

Where, X = CO_2 fixation rate [mol CO_2 d $m^{-3}d^{-1}$]; I = solar radiation [MJ $m^{-2}d^{-1}$], P.E = net photosynthetic efficiency [%], SV = Surface to volume ratio [m^{-1}] and E = energy required to reduce a mol of CO_2 to glucose [0.48 MJ $mol^{-1}CO_2$] (Rezvani et al., 2016).

The present scenario of environment and energy have various challenges of carbon sequestration using microalgae because it is complex multicomponent mechanism of biochemical interactions. Although structure of microalgae cell organelles and functional relationship and regulation among these somehow understand, the interactions of atmospheric factors and living factors are also significantly impacted on CO_2 utilization in the microalgae (Singh et al., 2016a,b). The carbon sequestration in microalgae in natural condition is low but flue gas provides enough CO_2 to microalgae for the sequestration because the availability of atmospheric CO_2 is challenge to fix and satisfy optimum level. Cheng et al. (2019) conducted a study on *Chlorella* sp. *(Cv)* and suggested that the metabolic responses of flue gas were depend on various specific genes. The optimized regulation of genes for oxidative phosphorylation, photosynthesis, sulphur metabolism, nitrogen metabolism and CO_2 fixation was positively impacted on flue gas utilization. The intracellular sulphur transport and nitrate reductase were consume to stimulate SOx and NOx utilization in the microalgae cell. It may lead the direct utilization of power plant's flue gas in microalgae cultivation and help to enhance the CO_2 sequestration using microalgae because flue gas pretreatment processes will increased the energy and cost for process. Similarly, bio-refinery concept and carbon taxation schemes can also help to promote new dimensions to microalgae flue gas bio-fixation from TPPs.

4.1. Influencing operational parameters

Microalgae have gained tremendous attention in this century because of the wide range of applications such as CO_2 sequestration, biodiesel and bio-molecules production. The estimated species of algae range from 350,000 to 1,000,000 but only 30,000 (approximately) species have been analysed (Bux and Chisti, 2016). There are various parameters that able to influence the microalgal carbon fixation from flue gas. Because flue gas composition depends on the nature of fuel used in TPPs. Microalgal actual bio-fixation of CO_2 from flue gas in various bioreactors with their growth parameters are also studied and lined up in Table 7 in summarised way. These parameters are as:

4.1.1. Bioreactors

Microalgal bio-fixation of CO_2 from flue gas requires a cultivation system which can provide controlled environment. The cultivation of the microalgae can be done in various ways but classified under the two

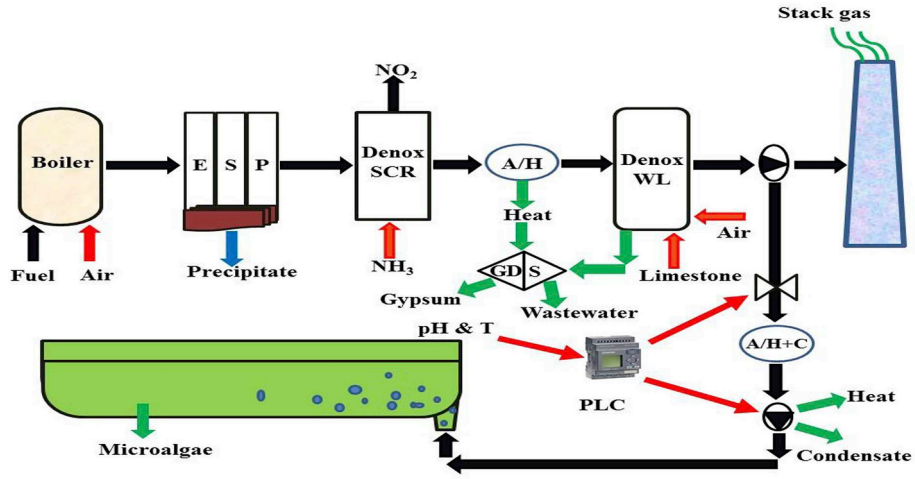

Fig. 4. Conventional process for microalgae based flue gas capturing from coal based thermal power plant. SCR: selective catalytic reduction; A/H: air heater; ESP: electrostatic precipitator; WL: wet limestone gypsum process; GDS: gypsum dewatering system; PLC: programmable logic controller (Van Den et al., 2012).

broad spectrums, which are open pond bioreactor and closed photo-bioreactor.

4.1.1.1. Open pond bioreactors. Open pond bioreactor has been used for the large-scale production of the microalgae and can be in any form such as naturally occurring water bodies like ponds, lakes and lagoons or manually constructed structures such as open tanks and raceway ponds. In open ponds bioreactor, the biomass production depends on the type of the species and configuration of the pond and the biomass produced each day per unit area gives the output of the open ponds. These are generally kept shallow so that the solar radiations can easily penetrate inside the pond (Majid et al., 2014; Goli et al., 2016). In India, Ministry of power promoted development of microlagal carbon fixation from TPPs flue gas. A pilot project at the 1260 MW Kolaghat coal-fired TPP captured 50% of CO_2 in the form of dry ice and rest to utilize in microalgae forming. Similarly, another 1200 MW Kolaghat coal-fired TPP captured 12% of CO_2. In this power plant, 728 m^2 open pond microalgal cultivation systems generated about 37–56 tons per hectare per year algal biomass. Similarly, in Israel, Rutenberg coal-fired power station constructed an open pond with 1000 m^2 and utilized flue gas with their constituent like heavy metals, SOx, NOx which were act as nutrients for algal growth and produced algal biomass was of food grade that can be used for feed as animal, fish**.** Furthermore, Taiwan Power Company had been developed and designed 30 tons photobioreactor system, an airlift photobioreactor and open pond system for flue gas bio-fixation through microalgae. Photobioreactor capable to fixed about 2.234 kg CO_2 by utilizing untreated flue gas of power plant. The air-lift photobioreactor utilized 13% of CO_2. Microalgae consumed CO_2 directly from coal-derived methanol and dimethylether and were converted into biodiesel and animal food in China (Zhang, 2015). A novel study conducted by Tastan and Tekinay (2016), in which they reported 2.262 g L^{-1} biomass accumulation rate by *Scenedesmus* sp. and CO_2 fixation rate was 1512.22 mg $CO_2{}^{-1}$ d^{-1} in lab scale open pond system (38 cm internal diameter, 40 cm height, 95 cm thickness), and a 26.17% higher calorific coal and algal biomass mixed “green coal” was also produced having lower ash content. Malek

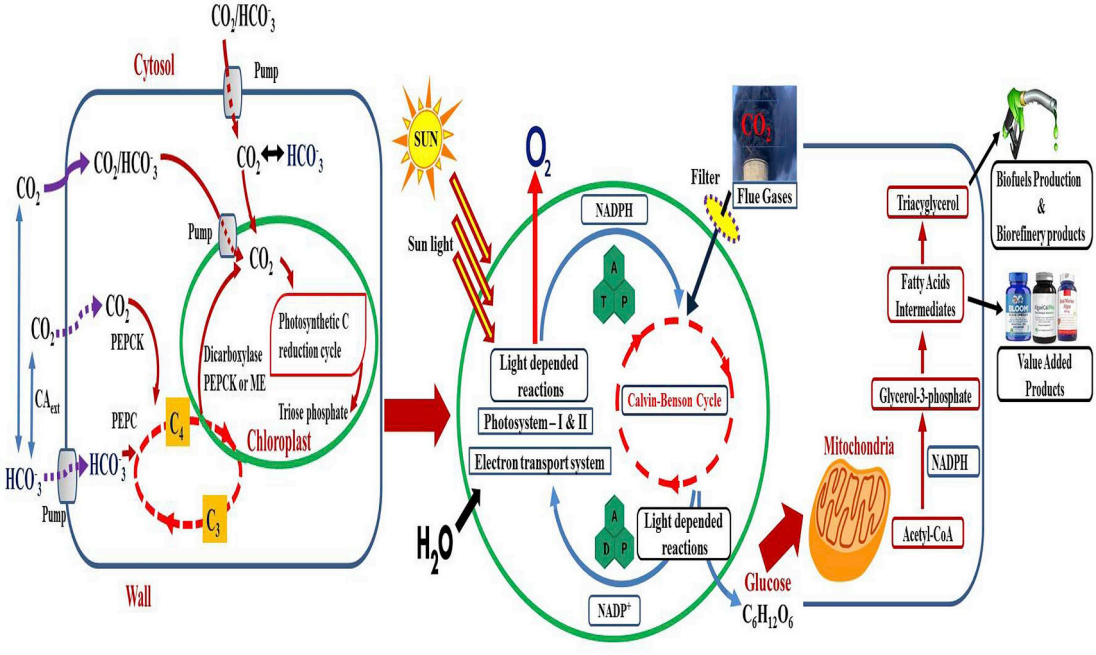

Fig. 5. Schematic bio-fixation of flue gas with microalgae: carbon concentrating mechanism and photosynthetic process. (Zhao and Su, 2014; Bhola et al., 2014).

Table 4
Chemicals utilized for flue gas treatment processes.

Treatment processes	Chemicals used	References
Dry systems	Lime Limestone Sodium Bicarbonate Calcium Hydrate Magnesium Hydroxide Activated Carbon	Cottrell (2016); Kedrowski et al. (2010); North London Waste Authority (2014); Löschau and Karpf (2015); Svoboda et al. (2016)
Semi-dry systems	Lime Limestone Calcium Hydrate Magnesium Hydroxide Activated Carbon	Cottrell (2016); Kedrowski et al. (2010); North London Waste Authority (2014);; Löschau and Karpf (2015)
Wet systems	Limestone Caustic Soda Sodium Hydroxide Ammonia Magnesium Hydroxide Activated Carbon	Cottrell (2016); Kedrowski et al. (2010); North London Waste Authority (2014); Löschau and Karpf (2015)

Table 5
Advantages of using microalgae for bio-fixation of flue gas.

Microalgae	Advantages	References
Chlorella fusca LEB 111	Additional gases such SO_2, NO and ash are positively catalysed at certain limit to growth parameters of microalgae.	Duarte et al. (2017)
Haematococcuspluvialis	Economic pH control system	Choi et al. (2017)
Mixed consortium	Fatty acid and biodiesel production	Aslam et al. (2018)
Scenedesmus sp.	Making coal additives which have low ash content and higher calorific value	Tastan and Tekinay, 2016
Scenedesmusobliquus	Heavy metals (As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Se and Zn) removal from flue gas	Napan et al. (2015)
Fresh water mixed culture	Potential to bear 100% unfiltered coal fired flue gas	Aslam et al. (2017)
Desmodesmusarmatus	Easy to acclimatize the metabolic with altering of concentration of flue gas	Guo et al. (2017)
Acutodesmusobliquus	Biohydrogen and lipid production	Correa et al. (2017)
Scenedesmusobliquus UTEX 417	Energy efficient process	Ekendahl et al. (2018)
Graesiella sp. *WBG1*	Flexible to indoor and outdoor culture conditions	Wang et al. (2018)

et al. (2017) modulated an open pond reactor for the dual applications of recovering waste heat from flue gas which produced during introduction of flue gas into microalgae culture in open pond. This study set new direction to microalgal bio-fixation of flue gas as well as power generation from waste heat of flue gas. An outdoor study had been conducted by Dineshbabu et al. (2017) for bio-fixation of CO_2 from flue gas in open tank reactor with 550 L capacity by *Phormidium valderianum* BDU 20,041. Here, C14 and C18 fatty acids accumulated with lipid content 12.74% was shown that potential suitability for biofuel and also observed fixation rate of CO_2, 56.4 mg C L^{-1} d^{-1}. *Scenedesmus obliquus* SA1 had shown CO_2 bio-fixation rate 97.65 mg L^{-1} d^{-1} and biomass accumulation rate was 1.39 g L^{-1} with culture CO_2 concentration 35% in a natural open pond type reactor (Basu et al., 2014). Open pond microalgae cultivation is low-cost solution of flue gas treatment because operational and maintenance required less technical expertise. The TPPs flue gas bio-fixation project is now growing and gaining attention of researchers as well as commercial scale throughout the world. But, the open environment is raising the risk of contamination and water evaporative losses, major challenges at practical level and produced algal biomass is used only for animal and fishes as a feed-stock instead of biofuel options (Table 8).

4.1.2. Closed photobioreactors

In contrast to the open pond bioreactors, closed photobioreactor for the microalgae cultivation is a completely different approach and deals mostly with the closed vessels. The photobioreactor comes in wide variety including tubular, flat panel, continuous or semi-continuous "V" shaped polybag systems, and many more. Photobioreactors are more prone to the climatic conditions and eliminate the issue of the predators or parasites.

The use of flue gas from the Duernrohr power plant in Austria to grow cyanobacteria in a closed serpentine photobioreactor. A bio-plastic (polyhydroxybutyric) produced from the biomass of cyano-bacteria and rest of the biomass used in the biogas and one ton CO_2 can generate 115 kg bio-plastic and 320 m^3 of biogas. East Bend station in

Table 6
Carbon fixation efficiency of microalgae: recent experimental studies.

Microalgae species	Photobioreactor	Carbon fixation Efficiency (%)	References
Monoruphidiumminutum	Flasks	90	Aslam and Mughal (2016)
Chlorella sp.	Sequential	85.6	Aslam and Mughal (2016)
Chlorella vulgaris	Airlift	80	Sadeghizadeh et al. (2017)
Scenedesmusdimorphus	Bubble Column	75.6	Yadav and Sen (2017)
S. obliquus	Airlift	67	Li et al. (2011)
Chlorella vulgaris	Bubble Column	54	Yadav et al. (2015)
Spirulina sp.	Tubular	53.29	Aslam and Mughal (2016)
Chlorella sp.	Open Pond	42	Bhola et al. (2014)
Scenedesmusobliquus	Tubular	28.08	Aslam and Mughal (2016); Wang et al. (2008)

Table 7
Influencing process parameters in microalgal based bio-fixation from flue gas with their growth parameters.

Species/Strain	Cultivation System/ Reactor	Culture Medium/ Operation Mode/Feed	Growth Rate	Carbon Fixation Rate	Supplied CO_2	pH	Light Intensity	Temperature	References
Anabaena sp.	Airlift, Bubble column	BG -11 Medium, Continuous Mode	1.13 g L^{-1}, 0.31 g $L^{-1}d^{-1}$	0.35 g L^{-1} d^{-1}, 1.45 g $L^{-1}d^{-1}$	5%, Air	——	120 (uE $m^{--1}s^{-1}$), ——	——	Nayak and Das (2013); Kumar et al., 2011
Aphanothece sp.	——	——	0.800 g L^{-1} d^{-1}	1.5 g L^{-1} d^{-1}	15%	8.0	——	35 °C	Klinthong et al. (2015)
Chlorella sp.	Airlift, Incubator, Pilot-scale, Vertical tubular, Erlenmeyer flasks, ——, Airlift, Airlift, Bubble column, Bubble column, Bubble column, Airlift, Open pond, Airlift column, Inclined Tubular, Bubble column, ——.	——, ——, Tris- acetate –phosphate Agar Medium, BG-11 Medium, ——, ——, Bold's Basal Medium, Bold's Basal Medium, Bold's Basal Medium/Semi-Continuous Mode Mode/ Pure Flue Gas, Continuous Feeding, ——, Modified Tap, ——, On-off Feeding/Pure Flue Gas/Batch Mode, ——, Continuous Feeding/Pure Flue Gas/Batch Mode, ——.	0.2446 d^{-1}, 0.64 g L^{-1}, 0.40 g L^{-1} d^{-1}, (0.18 +- 0.01) d^{-1}, 0.032 ± 0.006 g L^{-1} d^{-1}, 950 mg $L^{-1}d^{-1}$, 0.407 +_ 0.015 g L^{-1} d^{-1}, 0.350 +_ 0.014 g $L^{-1}d^{-1}$, ——, ——, 1.915 ± 0.12 g L^{-1}, 150 mg L^{-1} d^{-1}, ———, 67 mg $L^{-1}d^{-1}$, 1.47 g L^{-1} d^{-1}, 2500 mg L^{-1} d^{-1}, 0.087 g L^{-1} d^{-1}.	——, 96.89 mg L^{-1} d^{-1}, 0.8 kg of $CO_2{}^{-1}$ d^{-1}, ——, 5.86 ± 1.16 mg $CO_2{}^{-1}d^{-1}$, ——, ——, ——, 271 mg L^{-1} d^{-1}, 353 mg L^{-1} d^{-1}, 287 ± 7 mg $CO_2{}^{-1}$ d^{-1}, 251 mg L^{-1} d^{-1}, ——, 113 mg L^{-1} d^{-1}, ——, 4400 mg L^{-1} d^{-1}, 1.0 g $L^{-1}d^{-1}$.	(7.6 ± 0.8) %, 10%, ——, 50%, 2%, 2%, 10%, 15%, 5%, 4% (flue gas), 10%, 15%, ——, (10-13) %, 18%.	——, 7.5-9, ——, ——, ——, 7-8, 7-8, 6.8, ——, ——, ——, 10, ——, ——, ——.	1800 Lux, 450 (μmol m^{-2} s^{-1}), 531 (umol m^{-2} s^{-1}), 41.6 (umol m^{-2} s^{-1}), 2400 Lux, ——, 100 (umol m^{-2} s^{-1}), 100 (umol m^{-2} s^{-1}), 106.6 (umol m^{-2} s^{-1}), ——, ——, ——, 30 (umol m^{-2} s^{-1}), 200 (umol m^{-2} s^{-1}), ——, 150 (umol m^{-2} s^{-1}), ——.	(30+_2) °C, (30.0 ± 2.0) °C, ——, 30°C, (25 ± 2) °C, 35 °C, 30 °C, 30 °C, ——, ——, (28 ± 2) °C, ——, 30 °C, ——, ——, ——, 30 °C.	Sadeghizadeh et al. (2017); Kassim and Meng (2017); Pavlik et al., 2017; Duarte et al. (2016); Tastsn et al., 2016; Zhang (2015); Dineshkumar et al. (2015); Dineshkumar et al. (2015); Yadav et al. (2015); Zhao et al. (2015); Yadav et al. (2015); Kumar et al. (2014); Bhola et al.,2014; Borkenstein et al. (2011); Brennan and Owende, 2010; Douskova et al. (2009), Wang et al., 2008.
Chlorococcum sp.	Airlift	Bold's Basal Medium	0.314 +_ 0.011 g $L^{-1}d^{-1}$	——	2%	7–8	100 (umol m^{-2} s^{-1})	30 °C	Dineshkumar et al. (2015)
Chlorogleopsis sp.	——	——	40 mg L^{-1} d^{-1}	20.45 mg $L^{-1}d^{-1}$	5%	——	——	50 °C	Bermudez et al. (2015)
Desmodesmus sp.	Conical transparent polyethylene bags	BBM Medium/Pure Flue Gas	47.45 mg L^{-1} d^{-1}	——	10%	——	——	28 °C	Aslam et al. (2017)
Euglena sp.	Tubular	Batch Mode	153 mg $L^{-1}d^{-1}$	382 mg L^{-1} d^{-1}	10%	——	——	——	Bermudez et al. (2015)
Graesiella sp.	Circular culture ponds	Modified BG-11 Medium	——	0.26 g $L^{-1}d^{-1}$	15%	8–9	200 (μmol m^{-2} s^{-1})	30 °C	Wang et al. (2018)
Monoruphidium sp.	Flask	——	1.0 g $L^{-1}d^{-1}$	——	——	——	——	25 °C	Aslam and Mughal (2016)
Nannochloropsis sp.	Vertical bubble column, Raceway pond, Roux Bottles (RB), Raceway pond	Synthetic Wastewater/ Semi Batch Mode, Pure Flue Gas, Batch Mode, Industrial Medium	0.088 g $L^{-1}d^{-1}$, ——, 0.256 g $L^{-1}d^{-1}$, ——	——, 407 mg $L^{-1}d^{-1}$, 0.482 g $L^{-1}d^{-1}$, ——	8%, (11-14) %, ——, 13% (coal fired flue gas)	5.5-6.5, ——, 6.3, ——	——, ——, 168 (umol m^{-2} s^{-1}), ——	———, ——, 25 °C, ——	Razzak et al. (2015); Millán-Oropeza and Fernandez Linares, 2017; Zhao and Su, 2014; Zhu et al. (2014)
Phormidium sp.	Open tank	Ossein Effluent/ Unscrubbed Flue Gas	30 mg $L^{-1}d^{-1}$	56.4 mg C L^{-1} d^{-1}	——	7.5 ± 0.2.	——	——	Dineshbabu et al. (2017)
Scenedesmus sp.	Bubble column, Open pond system, Tubular, Airlift, Lab scale closed systems, Airlift, Bubble column, Open system, Rectangular, Airlift, Erlenmeyer flask	Modified BG-11/On-off feeding/Pure Flue Gas, ——, ——, Bold's Basal Medium/Domestic Waste –water, ——, Bold's Basal Medium, On-off Feeding/ Pure Flue Gas/Batch Mode, ——, Modified Bold's Basal Medium, Modified Soil Extract Medium, ——	3.63 g L^{-1}, 0.033 g $L^{-1}d^{-1}$, 0.10 g $L^{-1}d^{-1}$, 196 mg $L^{-1}d^{-1}$, 4.975+-0.003 g L^{-1}, 0.381 +_ 0.012 g $L^{-1}d^{-1}$, 485 mg $L^{-1}d^{-1}$, 1.39 ± 0.023 g L^{-1}, 110.9 mg $L^{-1}d^{-1}$, ——, 1.84 g L^{-1}	889 mg L^{-1} d^{-1}, 1512.22 mg $CO_2{}^{-1}$ d^{-1}, ——, 368 mg $L^{-1}d^{-1}$, 252.883+-0.001 g L^{-1}, ——, 889 mg $L^{-1}D^{-1}$, 97.65 ± 1.03 mg $L^{-1}d^{-1}$, 208.4 mg $L^{-1}d^{-1}$, ——, 0.288 g $L^{-1}d^{-1}$	15%, ——, 6%, 2.5% (CO_2 enriched gas), (13.8+-1.5) %, 2%, 15%, (15–35) %, 10%, ——, (0.03-50) %, ——	——, ——, ——, 6.8, ——, 7-8, ——, ——, ——	100 (umol m^{-2} s^{-1}), ——, ——, 3500 Lux, ——, 100 (umol m^{-2} s^{-1}), 100 (umol m^{-2} s^{-1}), 6000 Lux, 55 (uE^{-1}$m^{-2}$$s^{-1}$), 1000 (lux), 180 (uEm^{-2} s^{-1})	(25 ± 1) °C, ——, 30 °C, (25 +_ 2) °C, 25 °C, 30 °C, ——, ——, (25 ± 2) °C, 28 °C, (25 ± 1) °C	Yadav and Sen (2017), Jiang et al. (2013); Tastan and Tekinay, 2016; Aslam and Mughal, 2016; Nayak et al. (2016a,b); Basu (2016); Dineshkumar et al. (2015); Yen et al. (2015); Basu et al. (2014); Nayak et al. (2013), Li et al., 2011; Tang et al. (2011)

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Table 7 (*continued*)

Species/Strain	Cultivation System/ Reactor	Culture Medium/ Operation Mode/Feed	Growth Rate	Carbon Fixation Rate	Supplied CO_2	pH	Light Intensity	Temperature	References
Spirulina sp.	Vertical tubular, Tubular, Raceway pond, SDGC bubble column, Column,	Zarrouk Medium/ Semicontinuous Feeding, —, —, Zarrouk's Medium, Flue Gas	62.1 mg $L^{-1}d^{-1}$, 0.22 g $L^{-1}d^{-1}$ 0.027 $gL^{-1}d^{-1}$, 1.82 g L^{-1}, 0.45 g L^{-1}	—	—, 6%, —, —, 15%	—, —, —, —	41.6 (umol $m^{-2}s^{-1}$), —, —, —, 8000 Lux	30 °C, 30 °C, —, —, 25°C	da Rosa et al. (2015); Aslam and Mughal, 2016; Kumar et al. (2015); Kumari et al. (2014a,b); Cheng et al. (2017)
Thermosynechococcus sp.	Bubble column	—	2.7 d^{-1}	—	10%	—	10,000 + -350 (lux)	55 °C	Pires et al., 2012
Synechoccus sp.	Growth chamber	BG 11 Medium	0.18 ± 0.03 d^{-1}	—	10%	—	41.6 (μmol $m^{-2}s^{-1}$)	30 °C	Durate and Costa, 2017

Note: '—' represents 'Not Available'. Also, the values given are in the order of the references respectively.

the USA used high sulphur coal and TPP utilized their flue gas in a closed loop vertical tube photobioreactor that was an assembly of 19,000 L feed tank and 5700 L harvest tank. The algal biomass production was very good and 30–39 g m^{-2} d^{-1} range was achieved with average 10 g m^{-2} d^{-1}. The harvested algal biomass was had 42.47% carbon and rest of the volatile matter without trace elements (Zhang, 2015). Chen et al. (2012) developed a three-dimensional microalgae culturing photobioreactor composed of 2016 individual 15 L transparent polyethylene terephthalate containers with volume 30,240 L, acquired 100 m^3 of land area. In this photobioreactor, *Spirulina platensis* was used for bio-fixing 2234 kg of CO_2per annum and producing a water-soluble protein free polysaccharides that could be used healthy food additives. A vertical tubular photobioreactor with a capacity of 1.8 L, 600 mm length and 75 mm in diameter was applied for the coal-based thermoelectric power plant flue gas remediation. *Synechococcus nidulans LEB 115* was accumulated higher biomass compositions as: 9.8% carbohydrates, 13.5 5 lipids and 62.7% proteins and the nature of flue gas was 10% CO_2, 60 ppm SO_2, 100 ppm NO and 3.1% ash content (Duarte et al., 2017). In Germany, Niederaussem power station utilized greenhouse for the optimized growing conditions of microalgae in a 'V' shaped hanging bag type photobioreactor. The total area of the bags are 1000 m^2but erupted only 600 $m^2$and the fuel gas treated by FGD systems and dried; then introduced to microalgae in photobioreactor and about 6000 kg dry algal biomass was produced with bio-fixation of 12,000 kg CO_2. Similarly, Vattenfall's Senftenberg (Brandenburg) coal power station used 'Hanging garden' microalgae growing system with 50,000 L photoactive volume to investigate CO_2 fixation in biomass of microalgae (Zhang, 2015). Taştan et al. (2016) conducted a study in Erlenmeyer flasks on various growth factors like pH, flow rate of flue gas, photoperiod and concentration of chlorophyll of green microalgae *Chlorella* sp. for treatment of actual coal flue gas. Therefore, the close photobioreactors are best suited to cultivate microalgae for the treatment of flue gas from TPP. The optimized growth conditions can provide an optimal environment with proper light, nutrients and control flow rate of flue gas in the closed photobioreactor. Therefore, in the closed photobioreactors tubular types have more surface to volume and it can solve the problems by providing higher surface contacts. Similarly, flat plate photobioreactors can also be a solution of mass transfer and gas accumulation during the process of bio-fixation. The control conditions and contamination free environment can help to produce high-grade value-added products, these all are summarised in Table 8.

4.1.3. CO_2

Microalgae utilize the CO_2 for their growth in two stages: the absorption from the flue gases by the process of mass transfer or chemical reaction and the bio-fixation using the photosynthesis.

4.1.3.1. Absorption of CO_2. For microalgae growth, absorption of CO_2 could be done either in the water or alkaline solution. The water solution is a key factor for the cultivation of photosynthetic microalgae because of the low solubility of the carbon dioxide in the water. There are various factors affecting the growth of microalgae, including the residence time during the transfer of CO_2 in the water and the residential time during the utilization of CO_2 by microalgae. The various methods to overcome from these factors are also suggested by different researchers. There are three different inorganic carbon assimilation pathways, which microalgae can use, are: (i) direct assimilation by the plasmatic membrane, (ii) use of bicarbonates (enzyme carbonic anhydrase convert HCO^{3-} into CO_2) (Schipper et al., 2013) and (iii) direct incorporation of bicarbonates via plasmatic membrane (Jacob-Lopes and Franco, 2010). With the direct incorporation of flue gases in close photobioreactor systems, the pretreatment costs decrease but can impose problems such as high concentrations of CO_2 and high temperatures. Moreover, due to low mass transfer coefficient of CO_2, the mass transfer from gaseous state to liquid state is a major limitation in the cultivation of microalgae. The

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Table 8
Important feature of bioreactors involve in microlagal bio-fixation of flue gas: advantages and disadvantages.

Cultivation systems	Advantages	Disadvantages
Open pond reactors		
Natural pond	Minimum capital cost Lower water and energy foot print	Water percolation and evaporative losses Difficult to occurrence in periphery of thermal power plant Difficult to manage optimum culture conditions
Raceway pond	Require low construction, operation and maintenance cost Low energy foot print	Require large land area High risk of contamination Water evaporative loss Difficult to regulate temperature Poor mixing potential of light energy and CO_2 Low biomass production
Circular pond reactor	Require low construction, operation and maintenance cost Relatively high energy foot print Relatively high mixing potential of culture	High risk of contamination Water evaporative loss Difficult to regulate temperature Low biomass production
Closed Photobioreactor		
Tubular	Large illumination surface to volume ratio Low shear stress effect Suitable for outdoor mass culture Higher mixing potential of light energy and CO_2 Low risk of culture contamination High photosynthetic efficiency rate Low photoinhibition rate	High risk of fouling Required large land area Poor mass transfer rate High accumulation rate of O_2 Higher capital cost
Flat plate	Huge illumination surface volume Manageable light path High productivity of biomass Suitable for outdoor mass culture Low accumulation rate of O_2 High photosynthetic efficiency rate Low photoinhibition rate High mixing potential of light energy CO_2 Easy to maintenance and operate Low risk of culture contamination High photosynthetic efficiency rate Relatively low capital cost	Low illumination surface to volume ratio High photoinhibition rate Difficult to regulate temperature High hydrodynamics stress
Column	Easy to maintenance and operate Low energy foot print Relatively low capital cost Require low land area High photosynthetic efficiency rate Low photoinhibition rate High volumetric mass transfer rate High mixing rate High mixing potential of light energy and CO_2 High rate of biomass productivity	Small illumination surface volume Required high technical expertise High shear stress
V shaped hanging bag	Require low construction, operation and maintenance cost Required relatively less technical expertise High mixing potential of light energy and CO_2 Easy to harvest algal biomass Easy to maintain purity of culture Low energy foot print	Poor transparency of light Short life cycle of poly bag Relatively high shear stress Only indoor cultivation

limitations due to the mass transfer could slow down the growth rate, hence need to be overcome. This could be achieved by the high area of contact and high mixing (Pires et al., 2012). The surface area can be increased for mass transfer using the bubbling or absorption in the packet bed. But the bubbling process is more power consuming or may result in the damage of the algal cells (Vasumathi et al., 2012).

4.1.3.2. Fixation of CO_2. Carbon-fixation rate depends on the CO_2 residence time in the bioreactors. The more the time CO_2 presents in the reactor, the more the fixation done by the microalgae. Thus, in order to achieve higher fixation rate sufficient time should be needed. Fixation rate also depends on the temperature and the number of photons available to the microalgae. The absorption rate of CO_2 should be adjusted to the fixation rate, as fixation rate of CO_2 is fixed for any given operating conditions. This means that the time for absorption of CO_2 from flue gases by microalgae and the time required for fixation of CO_2 should be more or less same (Vasumathi et al., 2012). CO_2 bio-fixation from flue gas using algal biomass has a potential for implement, if the dissolved gas quantity increased beyond the natural condition (Kim et al., 2013). Use of chemical absorbents like alkanamide solution to capture CO_2 from flue gas is a common method and monoethanolamine (MEA) is the popular absorbent cited in literature in the process, but it is a high-energy consuming process (Muraleedharan et al., 2012; Moullec et al., 2014). So, different microalgae strains are susceptible for different tolerance levels of CO_2 concentration.

4.1.4. Light

To initiate the process of photosynthesis, light is a key ingredient as it is involved in the conversion of the CO_2 into the carbohydrates. In comparison with the plants, microalgae require the less intensity of light for its growth (Goncalves et al., 2014). Solar radiation is the main source of light but other sources like artificial lightning can be used for microalgae growth (Zhang, 2015). Solar radiation can be used on both type of bio-reactors (open/close) but with close type photobioreactors, artificial lightning is preferred. Similarly, use of solar energy can also be done in the closed photobioreactor where the fibre optics or solar concentrators can be used to maximize the effect of solar energy. It is estimated that only 43–45% of the total solar radiations are involved in the commencement of the process of photosynthesis, these radiations

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Table 9
Research trends and outcomes of microalgal bio-fixation of flue gas in recent five years.

Objectives	Technical Specifications	Outcomes	References
CO_2 bio-fixation and lipid productivity optimization in oleaginous microalgae *Graesiella* sp.	**Microalgae:** *Graesiella* sp. **Flue gas composition:** 15% CO_2 flue gas concentration. **Cultivation system:** 10 L circular pond and 5 m^2open raceway reactors	The maximum CO_2 bio-fixation rate at pH 8.0–9.0 The maximum lipid (0.26 g L^{-1} d^{-1}) and biomass productivity (18.9 gm^{-2}) obtained at pH 8.0–9.0. The positive correlation between CO_2 utilization efficiency and pH value	Wang et al. (2018)
Thermoelectric power plant CO_2 mitigation in culture in medium containing flue gas waste	**Microalgae:** *Synechoccusnidulans* **Cultivation system:** Acrylic vertical tubular photobioreactor **Source of flue gas:** coal based thermal power plant **Flue gas composition:** 10% CO_2, 60 ppm SO_2, 100 ppm NO **Photoperiod:** 12 h light/dark	Microalgae shown tolerance up to 200 ppm SO_2 and NO_2 with specific growth rate 0.18 d^{-1}. The coal ash content increased maximum cell growth 1.3 times. The optimum CO_2 bio-fixation efficiency was occurred 10% of CO_2, 60 ppm SO_2, 100 ppm NO and 10 ppm ash. The biomass contains 9.8% carbohydrates, 13.5% lipid and 62.7% proteins.	Duarte et al. (2017)
Biological CO_2 mitigation from coal based thermal power plant by *Chlorella fusca*and *Spirulina sp.*	**Microalgae:** *Chlorella fusca*and *Spirulina* sp. **Cultivation system:** close Erlenmeyer flask-type photobioreactor with 1.8 L working volume. **Flue gas composition:** 10–12% CO_2, 400 ppm, 5000 SO_X and 650 ppm ash **Source of flue gas:** coal based thermal power	Specific growth rate of *Chlorella fusca*is 0.17. *Chlorella fusca*2.6 times higher potential of CO_2 from coal flue gas than *Spirulina* sp. Bio-fixation of CO_2 rate was 68%. The microalgae isolated from coal power plant.	Duarte et al. (2017)
Acclimatization and selection of microalgae to growth in 100% unfiltered coal-fired flue gas	**Microalgae:** *Desmodesmus* sp. **Cultivation system:** twelve 30 L conical transparent polyethylene bags photobioreactors **Flue gas composition:** 100% unfiltered flue gas (11% CO_2) **Flue gas source:** Coal-fired flue gas pH**:** 7 **Photoperiod:** 16:8 h light/dark	100% unfiltered coal-fired flue gas tolerate microalgae identified. Phosphate buffering enabled growth in 100% unfiltered flue gas. Gradual adaptation can make possible to develop 100% unfiltered coal-fired flue gas. *Desmodesmus* sp. were most resilient and dominated microalgae in consortium	Aslam et al. (2017)
Optimization of flue gas and pure CO_2 for microalgae cultivation with recovery of waste heat recovery of flue gas	**Microalgae:** *Nannochloropsis salina* **Cultivation system:** Outdoor clay lined open pond **Flue composition:** 8% CO_2, 16% H_2O, 3% O_2 and 73% N_2 **Flue gas source:** Thermal power plant	Supply of unfiltered flue gas utilization for microalgae cultivation is economical as compared to purified flue gas. Waste heat recovery from thermal power plant heat Waste heat recovery involve high capital.	Malek et al. (2017)
Improvement of various degree of level of CO_2 bio-fixation in marine microalgae *Oscillatoria* sp.	**Microalgae:** *Oscillatoria* sp. **Flue composition:** 100% pure CO_2 **Cultivation system:** Flat plate photobioreactor with working volume 4 L **Photoperiod:** 12:12 h light/dark	Marine microalgae *Oscillatoria* sp. was able to sustain pure CO_2 up to 100%. Increased biomass yield of 44.7% observed. Higher supply of CO_2 has an impact on pH variation and resulted higher specific growth. Carbon utilization also increase with higher concentration of CO_2	Nithiya et al. (2017)
Development of coal additive form microalgae produced from thermal power plant flue gas	**Microalgae:** *Scenedesmus* sp. **Cultivation system:** Lab scale open pond **Source of flue gas:** coal based thermal power **Photoperiod:** 12 h light/dark	Microalgae tolerate 9.6 vvm of flue gas at 35 °C CO_2 bio-fixation rate was 1.51,222 g CO_2 day^{-1}. The novel coal additive also developed which have higher calorific value and lower emission. This strain was highly flue gas resistance because isolated from river near the thermal power plant.	Taştan, and Tekinay (2016)
Utilization of flue gas and their gaseous and solid constituents for cultivation of *Chlorella fusca*	**Microalgae:** *Chlorella fusca* **Cultivation System:** Vertical Tubular Photobioreactor **Source of flue gas:** Coal Power Plant **Flue gas composition:** 10% CO_2**,** 200 ppm SO_2 and NO and 40 ppm ash. **Photoperiod:** 12:12 light/dark	*Chlorella fusca* tolerated up to 400 ppm SO_2 and NO, this concentration also not affect to CO_2 bio-fixation Ash content of thermal power plant up to 40 ppm did not affect the cell growth Industrial wastes added to the cultures did not affect the biomass composition.	Durate et al., 2016
Techno-economic assessment of CO2 bio-fixation using microalgae	Theoretical assessment based on previous studies **Cultivation System:** Raceway pond and photobioreactor **Source of flue gas:** State-of-the-art power plants **Flue gas composition:** 4–14% CO_2 concentrations in flue gas.	Systematic analysis of microalgal bio-fixation of CO_2 Techno-economic analysis of power plants technologies with CO_2 bio-fixation. Microalgae pricing over $400 t^{-1} at higher photosynthetic efficiency	Rezvani et al. (2016)
Performance evaluation of microalgal bio-fixation CO_2 from of flue gas in closed photobioreactor.	**Microalgae:** *Chlorella* sp. **Cultivation System:** Bubble column photobioreactor **Source of flue gas:** Thermal power plant **Flue gas composition:** 0.04, 2.5, 5, 7.5, 10% of CO_2 concentrations pH**:** 6.8 **Photoperiod:** 12:12 light/dark	Biomass productivity improved 21–36% in 5% CO_2 concentration. Strategically well plan experimental study to minimize toxic effects of flue gas Bio-fixation efficiency of CO_2 was improved by 54%. Microalgal biomass was analysed for various application.	Yadav et al. (2015)
Optimization of microalgal bio-fixation of CO_2 in closed raceway photobioreactor	**Microalgae:** *Chlorella kessleri* **Cultivation System:** lab-scale closed raceway	*Chlorella kessleri* cultivated in oil sand process water.	Kasiri et al. (2015)

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Table 9 (*continued*)

Objectives	Technical Specifications	Outcomes	References
	photobioreactor **Flue gas composition:** 0.03–15% of CO_2 concentration	The study conducted in lab scale closed photobioreactor. Biomass concentration increase 1.5 fold and 2 fold in average CO_2 uptake rate in 240 cultivation hours. Develop a mathematical model for fed-batch algal culture.	
Optimized CO_2 bio-fixation in outdoor culture of *Chlorella vulgaris* in bubble column photobioreactors.	**Microalgae:** *C. vulgaris* **Cultivation System:** Bubble column photobioreactor with 80 L capacity **Flue gas composition:** 2%, 4% and 8% (v/v) CO_2 enriched air. pH**:** 6.5 **Photoperiod:** 12:12 light/dark	Tropical climatic conditions analysed Controlled CO_2 input conditions did not affect the algal growth and reduced 50% CO_2 input. Biomass conversion efficiency increased doubled. Higher carbohydrate occurred as compared to protein	Guo et al. (2015)
Cultivation of *Spirulina platensis* using a complex fertilizer NPK-10:26:26 in chromatographic glass bubble column	**Microalgae:** *Spirulina platensis* **Cultivation System:** Sintered disk chromatographic glass bubble column. **Flue gas composition:** 20–100% (v/v) CO_2 enriched air pH**:** 10 **Photoperiod:** 14:10 light/dark	Spirulina growth using sintered disk chromatographic glass bubble column. Biological conversion of CO_2 100% and biomass concentration of 1.83 gL^{-1}at fourth day Cultivation in complex fertilize NPK-10:26:26	Kumari et al. (2014a,b)
CO_2 bio-fixation by microalgae isolated from biodiversity hotspot of Assam, India	**Microalgae:** *Scenedesmus obliquus* **Cultivation System:** Erlenmeyer flasks **Flue gas composition:**13.8 CO_2 pH**:** 8.49 **Photoperiod:** 14:10 light/dark	An indigenous microalgae isolation from biodiversity hotspot. 13.5% CO_2 concentration tolerated at 40 °C temperature. Higher microalgal biomass accumulation. Microlagal biomass shown potential of value added products.	Basu et al. (2013)
Bio-fixation of CO_2 by cyanobacteria anabaena sp. in photobioreactor.	**Microalgae:** *Anabaena* sp. **Cultivation System:** Airlift Photobioreactor **Flue gas composition:** 5% (v/v) CO_2 enriched air	Bubble column and airlift photobioreactors comparison for CO_2 sequestration. Biomass concentration were 0.71 g L^{-1}in bubble column and 1.13 gL^{-1}in airlift photobioreacters Results was validated Gompertz equation.	Nayak and Das, 2013

are termed as Photosynthetically Active Radiation (PAR). About 27% of PAR is used by the microalgae for the conversion of CO_2 into carbohydrates.

The following equation established the rate of growth of biomass as:

$$P = \alpha \, E.I \quad (4b)$$

Where, P is the rate of production of dry microalgae and is measured in g m^{-2} d^{-1}, E is the efficiency of photosynthesis, I denotes light energy in $Kcal^{-1}$ m^{-2} d^{-1}, and the symbol α represents the conversion coefficient (g $Kcal^{-1}$) (Majid et al., 2014).

In artificial lighting systems, the use of light electric diode (LEDs) sources has shown more economic stability than the fluorescent lamps. The effect of light also depends upon other factors like temperature and nutrients. It is observed that under high temperature, low intensity of light is suitable for the growth of algal biomass. Also, under high light intensity, the nutrient concentration increases, thus increase in the microalgal photosynthesis and light/dark cycle are significantly influenced by microalgal growth (Kumar et al., 2011; Pires et al., 2012). Hence, use of LED lightning systems have long lifespan, and can also reduce cost and energy footprint.

4.1.5. Nutrients

Some of the main nutrients required by the microalgae for their growth are nitrogen, minerals, trace elements, various salt concentrations, etc. among these most of the available in the flue gas. These nutrients required by microalgae with optimized ranges are also present in the flue gas as per their compositional nature (Durate et al., 2016; Malek et al., 2017). For instance, some species utilized the nitrogen nutrition is available from the NO_X components of flue gas, thus in the same way, SO_X components can be used for the sulphur nutrition. Low concentrations of NO_X can be used as source of nitrogen nutrition by microalgae (Klinthong et al., 2015). Napan et al. (2015) performed broad study of the impacts of heavy metals from flue gas integration with microalgae production, in which ten heavy metals, (As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Se and Zn) at four different dose responses had been investigated on the *Scenedesmus* sp. The maximum lipid and growth rate was observed at two, five and ten fold of flue gas, and on average 87% Hg, 21% Se were absorbed by microalgae and the study also suggested that most of elements were redistributed in the biomass and may be in by-products.

Therefore, toxic heavy metals can also be used as nutrient supplement of microalgae. Although, most of the concentration of heavy metals redistributes in the medium, algal biomass and by-products, the remediation of heavy metals can be noteworthy from flue gas. The integration of wastewater and flue gas treatment can also be remarkable solution for both problems in which microalgae are consuming nutrients from wastewater and flue gas.

4.1.6. Concentration of growth medium

The growth of microalgae undergoes various stages at any concentration of the CO_2, light and nutrients which include lag, log, deceleration, stationary and death phase. One of the important parameters for the growth of microalgae is the initial concentration of the microalgae. The rate of the growth of the microalgae is directly related to the cell concentration. The growth rate increases up to the optimal concentration when the initial concentration of the microalgae is less as compared to the concentration of the light and CO_2 absorbed. After this, the rate of growth decreases with microalgae concentration as the continuous depletion of the CO_2 and the nutrient concentration outweighs the benefit of having more microalgae.

By harvesting the excess microalgae formed above optimal concentration, an optimum concentration can be achieved to achieve the highest rate of microalgae growth. This can be done in continuous process and thus can reduce the size of the bioreactor for a given

production rate (Vasumathi et al., 2012). Therefore, higher microalgal cell concentration can increase shading effect and reduce light penetration into culture medium, reduce nutrient availability which leads to words decline phase.

5. Recent research trends on bio-fixation of flue gas

There is a large number of research articles published in recent years on this concept. Among them most of are review articles with theoretical analysis and modeling articles, giving comprehensive information about contemporary world on the basis of various parameters at various degree of considerations such as Nayak and Das (2013); Roberts et al. (2015); Rezvani et al. (2016); Khichi et al. (2018). These studies provide base information before start experimental studies and evaluate technological, economic and biological parameters of microalgal bio-fixation CO_2 from flue gas technology and their associated challenges Table 9, enlisting various recent experimental studies about microalgal bio-fixation of CO_2, and objective of different studies, technical specification and their outcomes, which are reflecting current trends of this technology to make it more comprehensive on research part.

Currently, major microalgal bio-fixation of flue gas commercial projects of TPP based on open raceway ponds due to low-cost in most of the countries whereas at lab-scale, closed type photobioreactors is the first choice of researchers at global level, similarly, working mode majorly focused on CO_2 biofixation only, utilization of whole composition of flue gas is under the R&D with wastewater from TPPs also. Bubble column, air-lift flat plate and column closed photobioreactors are most suitable cultivation system for CO_2 bio-fixation but involved high capital cost. Therefore, these closed photobioreactors are not much used in direct TPPs at commercial scale. Hence, major part of research and development sector, flourishing the lab studies because easy to handling and their results are showing that the higher cost can be reduced over the time of period. Some marine (*Oscillatoria* sp., *Nannochloropsis salina*, *Graesiella* sp., *Synechoccusnidulans*) and freshwater species (*Chlorella vulgaris, Chlorella sorokiniana, Chlorella kessleri, Scenedesmusobliquus, Desmodesmus* sp.) are identified for utilization of 100% pure CO_2 gas and 100% unfiltered flue gas (with composition of 11% CO_2) [Fig. 6].

6. Concluding remarks with future recommendations

Present applied flue gas treatment processes and technologies are fundamental solutions which cannot able to lead towards sustainability due to involvement of higher energy inputs, cost and environmental considerations. Microalgae have ample potential for biological fixation of CO_2 from flue gas from TPPs, which can help to reduce carbon footprint of conventional power productions for clean atmospheric environment and in addition with by providing various new routes and functions to produce biofuel. Microalgal bio-fixation of carbon is an environmental friendly technology, work under optimized conditions of growth parameters in bioreactors. Furthermore, to make it more advantageous for future research, some recommendations are also formulated after extensive study of available literature, due to its integrated approach for clean air and water for future to produce various value-added products from algal biomass. Some specific future research perspectives are as:

- The impacts of coal based flue gas with heavy metals on the microalgal growth rate and lipid accumulation are not proper understandable, because one and two metal concentration has been studied, but flue gas has number of heavy metals, which can cause various effects on microalgal growth.
- The use of flue gas is an important resource for industrial phycology. Because, flue gas is rich in most of the macro and micro nutrients which are able to provide basic need of nutrition to microalgae with a standard dose. If exposure time and dose of flue gas investigate to set than the CO_2 of flue gas can manage towards innovative applications of microalgae biomass compounds. The carbon footprint of microalgal biomass production could significantly lower the cost and is also lower the remediation cost of CO_2.
- Temperature range for flue gas is 80°C-120 °C and conventional treatment process for cooling increase the cost but use of high temperature tolerant microalgal species *Chlorella* sp. (25 °C - 40 °C), *Scenedesmus obliquus* (30 °C - 40 °C), *Aphanothece microscopica* (35 °C - 40 °C), *Chlorogleopsis* sp. (50 °C), *Nannochloris* sp. (25 °C), *Nannochloropsis* sp. (25 °C) provides a new scenario for sustainable future for treatment. Furthermore, heat recovery tools can be used for further use of heat during the winter for algal growth when the temperature of growth medium is lower.
- Although power production from flue gas heat and CO_2 recovery, an integration of microalgae cultivation, is demanding with high capital investment, it can reduce the carbon footprint of TPP by proving valuable heat for other applications. This high cost can also be levelised by comparing with harmful impacts of GHGs.
- The bioreactor cost is another challenge for the bio-fixation of CO_2

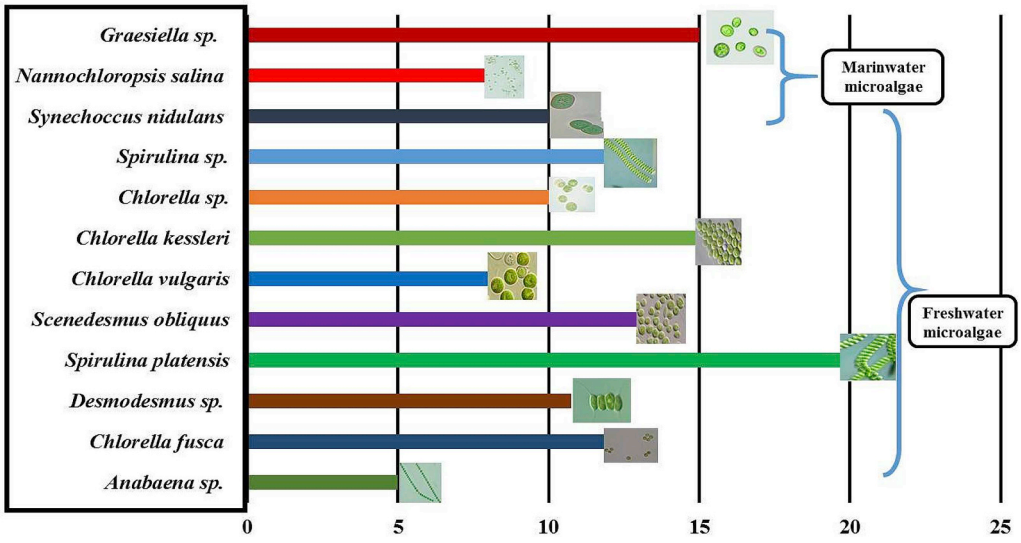

Fig. 6. Recently identified microalgae species and their percentage for bio-fixation of flue gas.

from TPP's flue gas. The open pond reactor has low cost as compared to closed photobioreactor. Similarly, the higher technical expertise also required the maintenance of close photobioreactor and in open pond reactor minimal need of these.

- The by-products of microalgae from utilization of flue are not pure, they have contamination of various toxic metals and compounds. Therefore, by-products cannot be utilized for direct human consumption and as an animal feed. In this regard, it is required to complete removal of the toxic metals from flue gas before introduction in the microalgae culture medium, so that algal by-products could be free from metal toxicity, will be a part of challenge for this intervention and needs proper research.
- The cost of cultivation microalgae is barrier to industrial level and the delivery of CO_2 is cost and energy-intensive process into microalgal cultivation. Because CO_2 from flue gas in gaseous phase needs to capture and compress gas, and most of microalgal open pond reactor and closed photobioreactor required water-soluble CO_2. The capture and compression process are enhancing the cultivation cost and energy footprint.
- The low carbon and higher heat content are rising of new dimensions of microalgal bio-fixation by producing of hydride coal from mixing of waste microalgal biomass and coal which can further applied in heating application.
- Identification of species from nearby coal-based TPPs contaminated water bodies may also be a potential source with genetic engineering provides a paradigm shift for higher tolerance of CO_2 from these point sources, also a part of future research.

Hence, this conceptual hypothesis framed and delineated in this article provides an innovative effort for “recent research trends of bio-fixation from flue gas” which is close glance of current research and development. It compiles technical specifications, challenges and outcomes of microalgal bio-fixation of CO_2 from flue gas with recent research articles because microalgae is a potential candidate for biological carbon fixation and sequestration to offset carbon emissions from point sources of emission in particular.

Acknowledgment

One of the author Har Mohan Singh is grateful to MNRE (Govt. of India) for providing the Senior Research Fellowship in the programme of NRE Fellowship at SoEM, Shri Mata Vaishno Devi University, Katra (J&K). Dr. V. V. Tyagi is also highly thankful to University Grant Commission (Govt. of India) for providing startup research grant at SoEM, Shri Mata Vaishno Devi University, Katra (J&K).

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